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Little (Arthur D.), Inc., Cambridge, MA

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16. ABSTRACT

This project included modifying an existing teleoperated robot to include autonomous navigation, large object avoidance, and air monitoring and demonstrating that prototype robot system in indoor and outdoor environments. An existing teleoperated "Surveyor" robot developed by ARD Corporation was modified to an autonomously navigated robot. A magnetic pick-up unit was installed on the "Surveyor" so that the unit could respond to and correct its course in relation to a high pressure electric puise travelling along a wire laid on the ground. The robot was also modified to carry a HNU PI-101 Photoionization Detector air monitoring device. A sonar range finder, which already was an integral part of the "Surveyor," was repositioned to the front of the robot chassis to detect large obstacles in the path of the robot. In addition, the software of the onboard computer was also extensively modified to provide: navigation control, dynamic steering to smoothly follow the wire-course without hesitation, obstacle avoidance, autonomous shut down and remote reporting of toxic substance detection.

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DEMONSTRATION OF AUTONOMOUS AIR MONITORING THROUGH ROBOTICS

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is reponsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of policies, programs and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides the vital communication link between the researcher and the user community.

The project described in this report addresses autonomous air monitoring at hazardous waste sites. The objective was to demonstrate the feasibility of autonomous air monitoring utilizing a commercially available robot with a minimum of modifications.

E. Timothy Oppelt, Director
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ABSTRACT

Investigation, mitigation and clean-up of hazardous substances often involve the performance of hazardous and/or tedious functions by on-site workers. These functions include site surveys, sampling, analysis, excavation and treatment and preparation of wastes for shipment to chemical disposal sites. Many times, important resources such as people working in the "hot" zone must leave their primary work on a frequent basis to perform the tedious task of monitoring the air at the perimeter of the clean-up site. The objective of this project is to conduct a field demonstration of air sampling (monitoring) utilizing a commercially available, field compatible robot with minimum modification.

The project demonstrated a robot which was modified to include autonomous navigation, large object avoidance and air monitoring. The prototype robot system performed each of the required tasks successfully in outdoor and indoor environments. Recommendations for additional modifications in an effort to develop a robot system which can be implemented in the field are included in this report.

This report was submitted as the final report for Work Assignment WA 3-51 under EPA contract number 68-03-3293 by Arthur D. Little, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from August, 1988 to March, 1989, and work was completed as of May, 1989.

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SECTION 1

INTRODUCTION

Investigation, mitigation and clean-up of hazardous substances often involve the performance of hazardous and/or tedious functions by on-site workers. These functions include site surveys, sampling, analysis, excavation and treatment and preparation of wastes for shipment to chemical disposal sites. Workers performing these functions risk dermal, ocular and/or inhalation exposure to hazardous chemicals. At many clean-up sites, important, and sometimes high-priced, resources such as people working in the "hot" zone will be taken away from their primary work each hour to perform the tedious task of monitoring the air at the perimeter of the clean-up site. Though tedious and time consuming, this work must be performed on a regular basis. Therefore, it would be very effective to have an autonomous device which could reliably perform this vital task at clean-up sites with a minimum of effort to setup and a minimum of effort to control the device once operational.

Robotic devices have been developed and used for a variety of functions including some involving hazardous environments, such as in nuclear power plants. The application of robotics to Superfund/SARA operations offers the possibility of increasing the level of personal safety of the workers by removing the worker from the potential for chemical contact or exposure to fire, explosion or other physical injury. Robotic devices also offer the potential of more rapid and reliable performance of tedious tasks which can quickly turn hazardous if the tedium causes carelessness on the part of the workers.

Over the last few years, the state of the art in robotics has progressed substantially, providing devices with improved capability in performing functions previously accomplished by humans. Although the potential of this technology for performing hazardous or tedious functions has been identified, no systematic attempt to determine the technical and economic feasibility of this application has previously been made.

As a part of the work assignment titled "Evaluation and Improvement of Personnel Protective Procedures for Hazardous Substance Response Operations", the EPA is exploring techniques and technologies which have the potential for improved safety and productivity. In FY 87 Arthur D Little, Inc. (ADL), under Subwork Assignment (SWA) 1-05-3 of this contract, performed a preliminary study of the use of robotics for improving safety and productivity in EPA hazardous response operations. ADL performed the following activities:

- Identified functions of critical interest to the EPA which represented opportunities for increased safety or productivity if automated.
- Identified robotic devices/procedures capable of performing those functions.
- Evaluated the technical and economic feasibility of implementing the devices/procedures in the field environment.

Ten hazardous or tedious functions were identified: Air Sampling, Bagging, Sampling Bulk Storage Tanks, Confined Space Entry, Soil Sampling-Boring, Soil Sampling-Test Pit, Bulking, Drum Sampling, Groundwater Sampling and Operating Excavation Equipment. We concluded that each of these, if automated, would provide improvements in productivity, or reductions in the hazard level encountered by personnel.

Each of the ten functions were analyzed and the Robotic System Requirements and a Conceptual Approach to implementing a robotic system were formulated. For several of the functions, examples of available robotic systems capable of performing these functions in a field environment were identified. The availability of these systems indicated the technical feasibility of applying robotics to these functions.

A representative application was selected to verify the technical feasibility and provide a basis for analyzing the economic feasibility of implementing these devices/procedures. The preliminary analysis indicated that the more hazardous functions would be more usefully automated. Subsequent discussions with EPA personnel revealed that the frequency of these functions coupled with a low incidence of injury makes them less desirable for automation than the tedious functions. Air sampling (monitoring) is a tedious function which is frequently performed in support of Superfund investigations, mitigations, removal and remedial operations involving hazardous substances. Since a platform suitable for the field environment and capable of supporting available air monitoring equipment was identified, and the Environmental Response Team (ERT) had independently identified air monitoring during Removal or Remedial Activities as a useful application of robotics, this function was chosen for demonstration.

SECTION 2

CONCLUSIONS

A demonstration of an air monitoring, autonomous robot was successfully performed indoors and outdoors. The robot, a modified Surveyor® designed by ARD Corporation, was guided by a magneto-strictive wire which was placed on the ground in two to three foot tall grass for the outdoor demonstration and on a warehouse concrete floor for the indoor demonstration. The tall grass and the uneven ground was a good test for the robot system and the system performed flawlessly. A photoionization air monitoring device was installed side-saddle on the robot to allow the monitoring device to discover and report concentration levels of a "toxic" substance as the robot followed the guide wire on the ground. Aluminum containers of paint thinner were placed along-side the wire and as the robot passed by the containers, the air monitoring device sensed the substance and the instrument's response was transmitted to a video monitor at the control station. The values were recorded by a video recorder in the control station so that they could be analyzed later. At the same time, a member of the demonstration team walked beside the robot with a hand held monitoring device and verbally announced the readings he took. His verbal responses were recorded by the video recorder as well. A comparison of the verbal responses and the signals sent by the robot-mounted monitoring device show that, except for one instance described below, the robot system recorded essentially the same levels of "toxic" substance in the air that the hand held monitoring device registered despite a very strong wind and cold temperatures. This validates the robotic system's successful performance.

TABLE 1. DEMONSTRATION ACTIVITIES SUCCESSFULLY PERFORMED

FUNCTION	OUTDOORS	INDOORS
Autonomous Navigation	X	X
Small Obstacle Navigation	X	X
Large Obstacle Avoidance	X	X
Air Monitoring	X	X
Stair Climbing	Not Tested	X
Decontamination	Not Tested	(a)

(a) Decontamination of the robot system was shown on video tape.

Table 1 summarizes the different activities that the autonomous robot system was required to perform and did perform successfully.

In addition to demonstrating the air monitoring function and autonomous tracking system, the robot was equipped with a sonar object detecting device which would stop the robot's forward movement if an object was detected in its path. This feature was demonstrated by placing a barrel on the guide wire and allowing the robot to advance towards the barrel. When the robot was approximately four feet from the barrel, it sensed that the barrel was in its path and stopped its forward movement, thereby successfully demonstrating the robot's obstacle avoidance system.

The robot also demonstrated its ability to traverse over small obstacles such as branches and rocks. Three small obstacles in the form of two-by-fours were placed across the guide wire. Each time the robot was able to drive over the obstacles and continue following the guide wire successfully demonstrating its small obstacle traversing capability.

A similar demonstration was performed in a warehouse using the same robot. A guide wire was placed on the floor of the warehouse and pans of paint thinner were placed along-side the wire. Once again the robot autonomously followed the path set by the guide wire. As it passed by the containers of paint thinner, the air monitoring device sensed the "toxic" substance in the air and reported the level to the control station. One of the demonstration personnel walked beside the robot taking measurements with a hand-held monitoring device and verbally announced the readings. Each of the readings were recorded by a video recorder for later analysis. The readings show that the two sensors recorded very similar levels of "toxic" substance in the air.

The obstacle avoidance and obstacle navigation capabilities were tested indoors in the same way that they were outdoors. Tall obstacles were placed on the guide wire and when the robot was within four feet, it was commanded to stop by the obstacle avoidance system. Smaller obstacles represented by four foot long wooden two-by-fours were placed across the guide wire and the robot drove over them and continued to follow the guide wire. On one occasion the robot lost track of the guide wire and came to a stop. The reason for this minor malfunction is believed to have been caused while transporting the robot from the outdoor demonstration to the indoor demonstration. One of the guide wire sensors was inadvertently struck and knocked out of calibration. Because this was a demonstration and the robot system a prototype, the guide wire sensors were mounted outside of the body of the robot and were susceptible to being damaged. In a production robot, those sensors would be installed inside the body of the robot out of harms way.

The final demonstration of the robot system was the task of climbing stairs. Portable wooden stairs used at the warehouse were used to show the ability of the robot system to climb stairs. This task was performed successfully. The robot first climbed the stairs, performed some camera maneuvers such as tilt and pan and then descended the stairs to the concrete floor.

During the demonstrations, a few areas where additional modifications to the prototype robot system could be made in order to make it a field implemented robot were identified. Table 2 lists these areas. A discussion of these areas can be found in the Section 3, Recommendations, and Section 5, EPA Robot Specifications.

TABLE 2. AREAS OF MODIFICATION FOR EPA ROBOT

Areas Identified
Navigation
Run Duration
Communication
System Operation

To summarize, a successful demonstration of an autonomously guided robot used to perform air monitoring of "toxic" substances was performed both indoors and outdoors. It was shown that an existing robot platform could be modified to perform tedious yet important tasks by adding specific sensors to the robot and tying them into the communications system of the robot.

SECTION 3

RECOMMENDATIONS

While demonstrating the autonomous air monitoring system, several areas were discovered where further modifications to the existing robot platform should be made before it can be implemented as a field robot. Table 2 lists the areas where additional modifications can be made.

It is recommended that the following modifications be made in order to improve the Surveyor's utility in the field:

- Investigate and develop an active suspension for all terrain use,
- Change drive motors, increase motor speed and add reduction gears to increase vehicle speed from 1 foot per second to an operator specified 1-10 feet per second,
- Upgrade onboard micro-processor to an 80286 or 80386 class machine, depending on processing requirements,
- Modify software to relocate the guide wire and to continue on course if obstruction is cleared,
- Investigate longer runtime options of a battery cart or alternative propulsion system. Specific EPA requirements, cost of modification and near-term ability to implement the choice should drive the selection of propulsion system.
- Develop a "leaky cable" communication system to replace the telecommunications currently used.

The above mentioned enhancements and modifications to the prototype system have been selected because they represent the major advances necessary to make the prototype system a field implementable system. They are enhancements and modifications which can be successfully made with a high level of confidence. Further descriptions of the bulleted items can be found in Section 5, EPA Robot Specifications.

Additionally, it is recommended that a demonstration of the prototype system with the above mentioned enhancements and modifications be held at a hazardous waste site, chosen by or under the direction of the EPA, to validate the autonomous robot's utility under actual site conditions.

SECTION 4

APPROACH

INTRODUCTION

The objective of this work was to conduct a field demonstration of air monitoring utilizing a commercially available, field compatible robot with a minimum of modification. The robot that was selected for use in the field demonstration was the ARD Surveyor®. The Surveyor®, shown in Figure 1, is a tracked vehicle equipped with a simple robot arm, an inspection optics system, a self contained power supply system and remote-controlled cameras for teleoperation. The robot was modified so that it could navigate autonomously, continuously and autonomously monitor the air and detect large objects and stop its forward motion.

The approach taken to demonstrating an autonomous air monitoring robot was to use an existing teleoperated Surveyor® robot like the one in Figure 1, developed by ARD Corporation, and modify it to make it an autonomously navigated robot. The robot was also modified to carry an air monitoring device and to stop if a large obstacle was in its path. Six tasks were identified to perform this work. Table 3 lists the tasks. Each task is described briefly here.

TABLE 3. WORK ASSIGNMENT TASKS

WORK ASSIGNMENT TASKS
Modify and Assemble System
Develop Performance Demonstration Plan
Test and Integrate Air Monitor
Perform Demonstrations
Develop Robot Specifications
Documentation

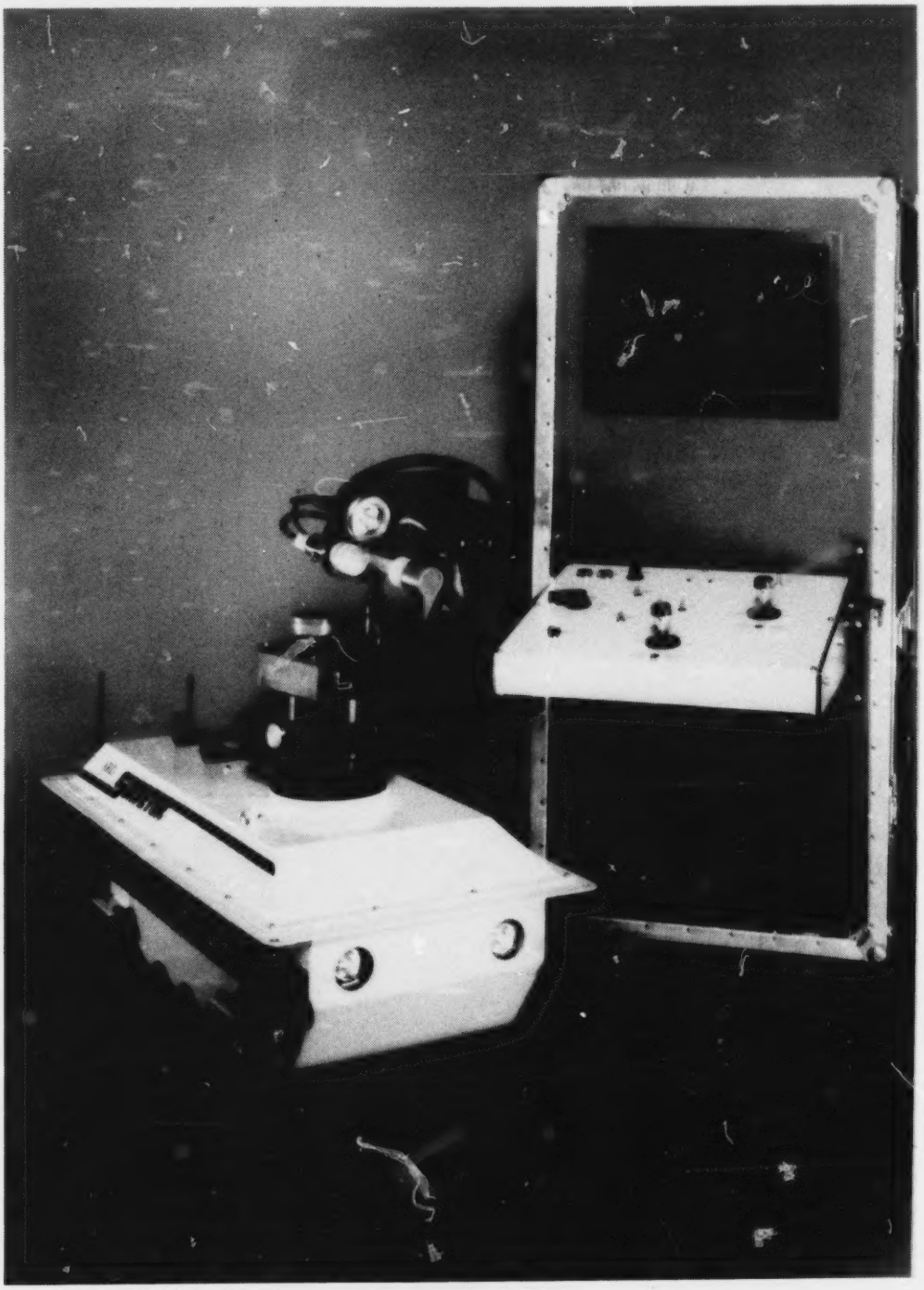


Figure 1. ARD Surveyor® robot and command console.

Task 1: Modify and Assemble System

The existing Surveyor® robot was modified to allow autonomous navigation around the perimeters of two sites, one indoors and one outdoors. A magnetic pick-up unit was installed on the Surveyor® so that the Surveyor® could respond to and correct its course in relation to a high pressure electric pulse travelling along a pre-wired path. The wire is simply laid on the ground. The technique used here is similar to tnat used in guiding autonomous vehicles around factory floors. Software to control the motion of the robot was developed and installed in the onboard computer.

The sonar range finder, which already was an integral part of the Surveyor®, was repositioned to the front of the robot chassis and was used to detect large obstacles. Once an obstacle was detected, and it remained detected for a predetermined period of time, motion of the robot was stopped so that no one and/or nothing would be run over by the robot. A mid-task review meeting was held at ARD's facilities in Columbia, MD. At that time a breadboard prototype of the navigation system was demonstrated and preparations for the demonstration were discussed. Details of all the modifications made to the Surveyor® can be found in Section 4, Robot System Definition.

Task 2: Performance Demonstration Plan

The Performance Demonstration Plan titled "Air Monitoring Autonomous Robot System Demonstration Plan" was written, submitted and approved in December, 1988. It contained a detailed description of the demonstration to be held later that month. Presented in the plan were the proposed sites and layouts of the course at each site, choice of the monitor, descriptions of demonstrations of the robot's capabilities and the measures of success for each capability to be demonstrated.

Task 3: Test and Integrate Sensor

An air monitoring sensor was selected based on work performed under this contract in Work Assignment 2-120 and on conversations with Robert O'Neil and Kenneth Menzies, two of the people who participated in that work. The HNU PI-101 Photoionization Detector shown in Figure 2 was selected. The monitor was sent to ARD so that they could design a bracket for it and install it on the Surveyor®. Details of the testing and integration of the monitor are discussed in Section 4, Robot System Definition.

Task 4: Demonstration

The demonstration of the robot system was held on December 15, 1988 at the EPA's Research facility in Edison, New Jersey. The demonstration began with a presentation describing the objectives of the work assignment and a description of the robot system and its capabilities, including the modifications for this work assignment. Suggestions on additional modifications were presented and open discussions followed several of the suggestions. Approximately 30 people from the EPA were in attendance. The attendees were then instructed to go to Building 245 to see the demonstration of the robot. One demonstration was performed outdoors on a cool, windy day in a field overgrown with two to three foot grass. A second demonstration took place indoors on a concrete floor in Building 245. There, in addition to performing its autonomous capabilities, the robot demonstrated its ability to climb and descend stairs.

After the demonstrations, a video tape of previous demonstrations of the Surveyor® and of decontamination procedures for the Surveyor® were shown. The details of the demonstration activities can be found in Section 5, Robot System Demonstration.

Figure 2. HNU PI-101 Photoionization Detector installed on robot.

Task 5: EPA Robot Specifications

Section 5, Field Robot Specification, describes some recommended modifications which will allow the robot system to be utilized in routine field operations. Based on the suggestions made during the demonstration presentation and in additional conversations with EPA personnel, the modifications described here will address real time telemetry of data, travelling speed of the robot, four wheel all terrain vehicle suspension for the robot and long duration power for the robot with minimum down-time for replenishment.

Task 6: Documentation

Throughout this work assignment, monthly reports have been submitted to the EPA describing the progress of the work being performed. In addition to this final report, a project summary report was prepared and two papers or articles will be prepared for publication. A 15 minute video tape of the demonstration is included as a deliverable along with the final report and project summary.

ROBOT SYSTEM DEFINITION

The Advanced Research Development Corporation (ARD), located in Columbia, Maryland, sells as a standard commercial product, the Surveyor® III robotic vehicle depicted in Figure 1. This section of the Final Report reflects the baseline description of the Surveyor® III Robotic Vehicle prior to making the modifications requested by ADL.

Introduction

The Surveyor® Mobile Surveillance System is a wireless, remotely operated vehicle. Table 4 lists the key characteristics which make the Surveyor® ideally suited for use at a hazardous waste site.

TABLE 4. KEY CHARACTERISTICS OF SURVEYOR®

Key Characteristics
Rugged and waterproof construction
Modular design for simple maintenance and improved availability
Easily decontaminated
Hardened electronics
Simple installation
User-friendly operator interface

An Overview of Surveyor® as a Mobile Teleoperated Robotic Device

Mobile teleoperated robotic devices can be used to inspect, monitor, locate, identify and/or maintain remotely located components and items as well as act as mobile surveillance devices while monitoring various environmental parameters/conditions such as temperature, humidity, and radiation. To be useful as an air monitoring system, mobile surveillance devices must also be capable of detecting the presence of airborne toxic substances. For purposes of discussion, mobile teleoperated robotic devices, including Surveyor®, can be subdivided into the seven subsystems or functions listed in Table 5.

The Surveyor® system consists of a remotely operated or autonomous vehicle that communicates through a signal or data communications system to a remote control station that serves as the operator's interface. The Surveyor® vehicle is primarily a tracked mobile platform that provides the mobility and propulsion functions necessary to move about the remote environment, although a wheeled suspension such as an all-terrain vehicle one can also be utilized. The robot system can include one or more manipulator systems which provide the kinematic and dynamic dexterity to perform work, although this is not part of the normal system configuration when

TABLE 5. ROBOTIC DEVICE SUBSYSTEMS

ROBOT SUBSYSTEMS
Locomotion/Propulsion
Power supply
Command/Data Communications
On-board Sensory and Related Equipment
Controls and Electronics
Computational Support
Command and Control

used in a surveillance function. Surveyor® also includes a remote sensing subsystem that gathers data retrieved by onboard sensors for the end user. This is the key area where we modified the Surveyor® system to extend or enhance its basic functions to include air monitoring, autonomous navigation and obstacle avoidance.

The controls and electronics subsystems and the data communications subsystem constitute the bi-directional information linkage between the electronics and electro-mechanical functions of the vehicle and the controls and displays of the human-machine interface. This linkage is, to a great extent, the essence of the mobile teleoperations.

The fundamental design requirement for Surveyor® in the role of an air monitoring mobile robotic system is one of being a self-propelled vehicle with provisions for computer control of task management, resource allocation, function (air monitoring), and navigation (including obstacle avoidance). The system is designed to be capable of carrying over five hundred pounds of payload and is typically configured with approximately one hundred pounds of sensors and fifty pounds of special purpose hardware. This could include:

- Special purpose cameras and lights for vision or data collection,
- Infrared, sonar, tactile, or laser sensors for proximity or range determination as well as obstacle avoidance,
- Additional on-board processing for local control or data reduction,
- Communication for monitoring, remote control, and off-board processing,
- Manipulators for actively modifying the environment,
- One or more sensors for air sampling/monitoring,
- A magneto-strictive or alternative autonomous navigation system,

- Off-board processing may include automatic object recognition, alternative navigation routines, and path planning routines.

The vehicle is relatively simple to operate, control and maintain. It is flexible enough to be used indoors, outdoors and in as much as fourteen inches of water before the antennas depicted in Figure 3 become submerged and communication is lost. The system can also be controlled in a tethered mode. Surveyor® is capable of carrying a variety of support and sensory equipment. Calibrated steering and travel is a fundamental capability to ensure accurate movements and navigation. Considering the computation time necessary for autonomous navigation and given the current onboard computing power of the Surveyor®, speeds over five to ten miles per hour are not advised and are probably unnecessary in an air monitoring function. A more powerful onboard computer could be used if speeds over ten miles per hour were required. The system demonstrated at Edison, New Jersey in December 1988, was governed (through hardware and software) to a maximum speed of 0.7 miles per hour. Though this is a slow speed for a field-implemented robot system, it was acceptable for the demonstration given the minimum of modifications to be made to the system. By changing the tracked propulsion system to an all terrain vehicle (ATV) four-wheeled suspension propulsion system, the field-implemented robotic system will be able to travel at speeds in the three to five miles per hour range (normal walking to a slow jogging speed).

Design of the Surveyor System

The Present Design--

The current Surveyor® Mobile Surveillance System is a computer-based, wireless, remotely controlled environmental surveillance/maintenance system. It is designed to meet specific guidelines to minimize occupational exposure to hazardous environments. Sensors, including radiation, temperature and relative humidity are used to obtain data from the environment. Zoom inspection optics read gauges, labels and position indicators, and inspect details in the surrounding environment. Auditory sensors monitor equipment and system performance. Figure 4 shows an exploded view of the Surveyor® with the additional sensors that were installed for this work assignment.

The operator guides the mobile vehicle from the Supervisory Control Station shown in Figure 1 using a stereoptic viewing system which greatly enhances operator's depth judgment and system control, permitting reliable operations in small, cluttered, unfamiliar and/or poorly illuminated spaces.

Mounted on one of the two robotic arms, as shown in Figure 3, the scanning inspection optics can be pointed in any direction and permit both wide-field and close-up viewing of remote objects, providing the operator with greater flexibility and capability than if on-site. Sensor outputs, including radiation, temperature, relative humidity and position/ranging, are continuously transmitted from the mobile vehicle, processed and displayed on the Supervisory Control Station. Advanced graphic representation of this data is displayed on the monitors at the control station and recorded on a VCR for subsequent analysis. This feature was widely used during the demonstration to the EPA in December to record the actual demonstration through the drive cameras of the vehicle and to record the output from the air monitoring sensor in real time. Vehicle operating and subsystem status data are computer processed and also displayed in real time on the color data monitor and recorded on the VCR.

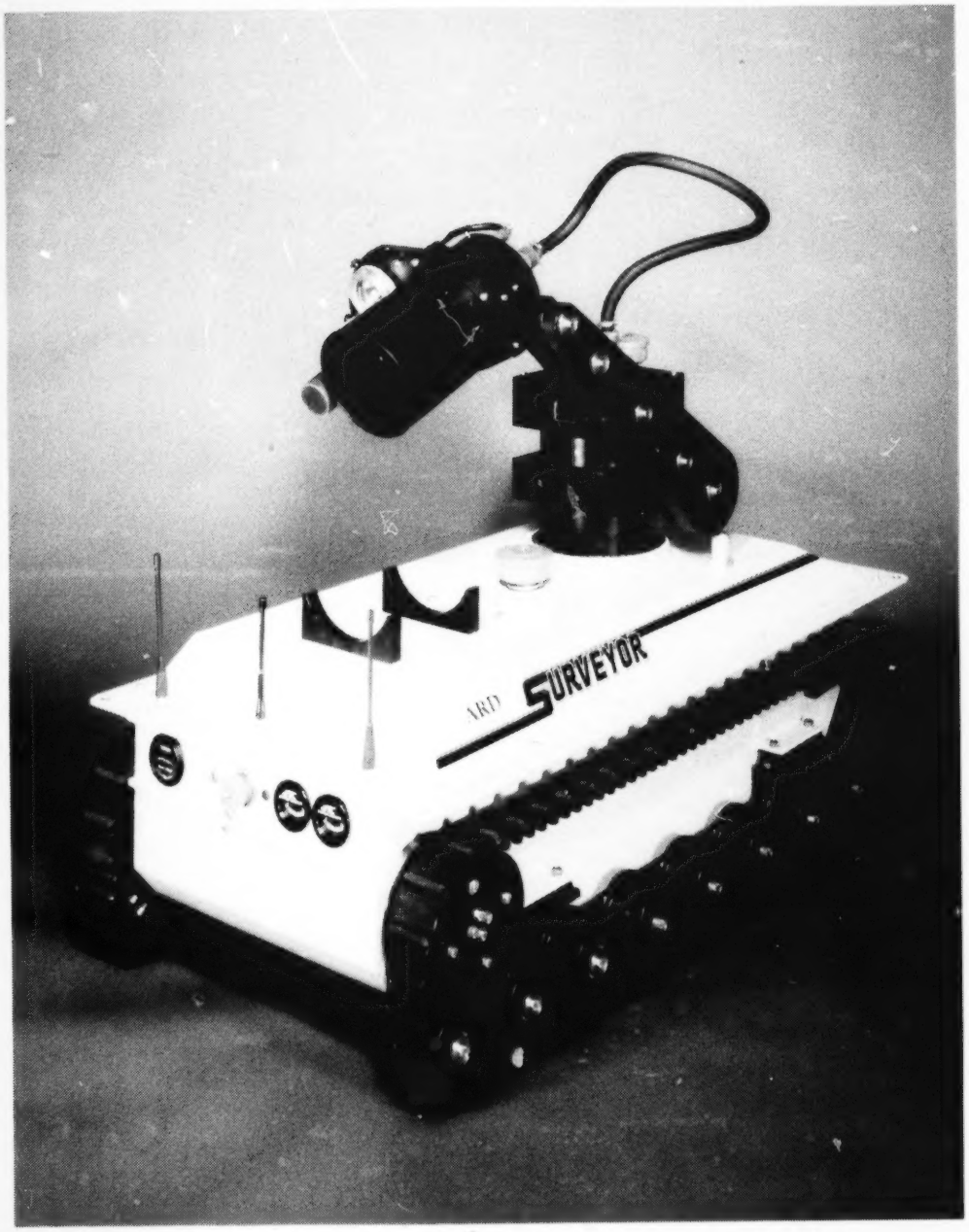


Figure 3. Rear view of Surveyor® III showing the rear panel and antennas.

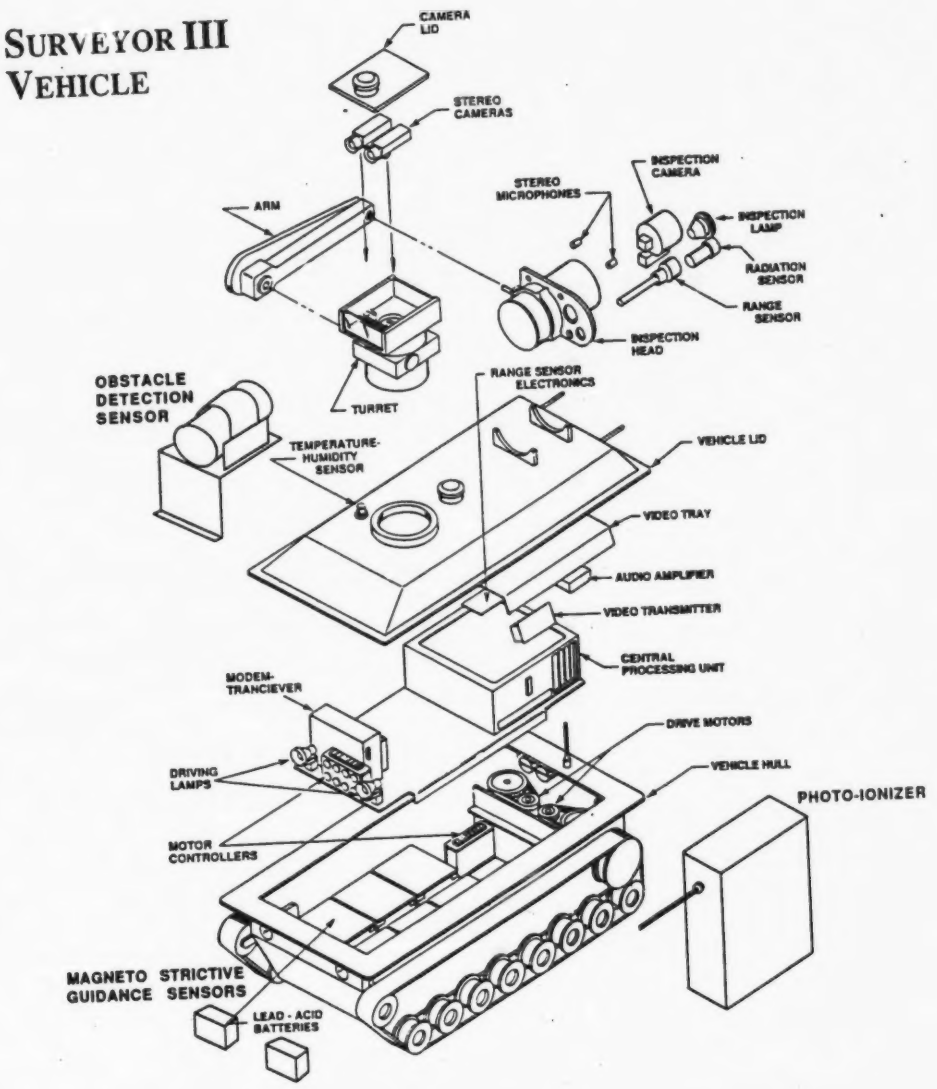


Figure 4. Exploded view of Surveyor® III with sensors installed.

The modular design of the Surveyor® System incorporates the following basic building blocks:

- The propulsion subsystem consisting of power and drive elements,
- The top cover, that houses the electronics and supports payloads,
- The payloads (inspection optics and sensors), and
- The electronics deck on which the video communication, command/control electronics, data systems and the power control systems are mounted.

Propulsion Subsystem--

The propulsion subsystem includes the chassis, batteries, motors, gear boxes, drive wheels, road wheels, tracks and track tensioners. The subsystem is sized for the tracks to span three stair risers on a 9.5" x 9.5" 40-degree stair.

Chassis--The chassis is welded steel plate. Provision is made for seven road wheel stub shafts on each side to be threaded into an independent chassis. The chassis is a separate subassembly and is shock-mounted to the hull. One upper drive wheel is mounted on each side at the rear. The front idler is part of the tread tensioning device.

Batteries and Motors--The batteries and motors are placed on or near the bottom of the chassis to keep the center of gravity as low as possible, which is essential for stairclimbing stability. Four sealed lead-acid batteries are used for power and are located forward on the bottom of the chassis. The two DC, 1/3 hp drive motors are frame mounted low in the chassis and provide power to the gear boxes through timing belts.

Gear Boxes--Two gear boxes are positioned to control the drive wheels located high and at the rear of the chassis. Speed Reducers are used to restrict the speed of any Surveyor® destined for use at hazardous waste sites.

Drive Wheels--The drive wheels, mounted on the gear box shafts at the upper rear of the chassis, are power pulleys with 0.5" bore.

Road Wheels--The seven road wheels on each side of the vehicle support and guide the tread and provide the (essentially) flat, straight surface required to span three stair treads. The road wheels are machined Delrin.

Treads--The tread provides positive traction on a wide variety of surfaces, including steel and concrete. The aggressive cleat design also permits operation on steel grating.

Tread Tensioners--The tread tensioner combines the tensioning mechanism with the front idler wheel. The design provides for the natural stretch in the tread and also incorporates a shock-absorbing spring.

Top Cover--

The vehicle's top cover is a simple straight-edged box with bottom flanges that mate with chassis and electronics deck.

Hull--

Video transmitting antennas and command receiving antennas are mounted on the top at the rear of the hull. An hour-meter and battery capacity meters and battery charging connector are located on the rear vertical surface.

Payloads--

The vehicle is designed to accommodate many different payloads and has command/control and data subsystem electronics to support them. The standard vehicle is configured with stereoptics, inspection optics, radiation, temperature, range and relative humidity sensors.

Stereoptics--

The stereoptics are both an operating subsystem (used for driving and positioning the vehicle while in the teleoperated mode of operation) and a payload that provides high-resolution visual data for surveillance. Two Charge Couple Device (CCD) cameras are used in conjunction with an auto-iris lens system that provides a 5.7 mm, wide-angle view from each camera. This subsystem is mounted on top of the arm/turret assembly. The cameras are focused and converged to meet four feet in front of the vehicle. Optic separation is approximately that of an adult with average vision. A rear-view CCD camera is also provided.

Inspection Optics--

The inspection optics consist of a CCD camera and a 10:1 zoom lens mounted in a waterproof housing. The lens has an auto-iris and is remotely zoomed and focused by the operator at the control console. This installation is mounted on the articulated arm which provides elevation (tilt) and horizontal rotation (pan). The camera and housing also rotate about the camera's transverse axis to provide a nodding motion. These combined motions provide great flexibility in camera positioning and permit viewing from straight overhead to down at the vehicle treads.

Environmental Sensors--

Three continuous reading, environmental sensors are mounted on the surveillance camera housing. The radiation sensor is a low range (gamma only) detector used in conjunction with a digital ion chamber. Temperature and relative humidity sensors are combined. Two extremely sensitive miniature microphones are also provided. Provision is made for interfacing up to thirteen additional sensors. This is one of the most important aspects of the design of the vehicle which made it possible to add the four sensors required for the EPA demonstration (two magneto-strictive guidance sensors, a photoionization air monitor and an obstacle avoidance sensor).

Electronics Deck--

The electronics deck supports all vehicle electronic subsystems including the video communications, the data subsystem, the command/control subsystem and the power regulation.

Video Transmitters--Two transmitters are used to transmit the video data. Each transmitter also has the ability to transmit audio or other data over the sidebands. One transmitter is used in this way to transmit the environmental and vehicle status data.

Data Subsystem--The data subsystem includes an analog-digital converter, a microprocessor and a modem. Data from the sensors are digitized, formatted into a serial bit stream by the microprocessor, and routed to the modem which sends it to the subcarrier oscillator and transmitter.

Command and Control--The command and control subsystem includes the receiver, servos and relays. Command signals sent by the operator from the SCS control console are received by an onboard computer and sent to the appropriate relay to apply a voltage to one of the devices being controlled (e.g., camera zoom or focus).

Power Subsystem--Electrical power from the 24V batteries is converted by power supplies into a series of voltages ranging from -12V DC to +24V DC and distributed to the proper components. Batteries are recharged through an external connector located at the rear of the hull.

Hardware Modifications

We made use of four of the thirteen expansion ports provided in the Environmental Sensor module of the Surveyor electronics platform on the mobile portion of the system to integrate the two magneto-strictive guidance sensors, the photoionization sensor and the obstacle avoidance sensor necessary to meet the requirements of this work assignment. In addition to the electrical interfaces, physical mounts were constructed for the hardware and attached the sensors to pre-existing mount points. This prevented altering the system's water tight integrity which would have occurred if new hull penetrations had been necessary. Surveyor® is already rated as water tight to ten feet, although the practical limitation of the height of the communications antennas prevents the use of Surveyor in more than fourteen inches of water. The software of the onboard computer was extensively modified to provide autonomous navigation control, dynamic steering to smoothly follow the wire-course without hesitation, obstacle avoidance, autonomous dead man shut down and toxic substance detection.

Magneto Strictive Navigation System--

The design and development of the magneto-strictive navigation sensors constituted the greatest technical challenge of the program. Although this is not a new concept, all the known cases of the use of this technology has been indoor applications with an imbedded cable placed approximated 1/2 inch below the surface of a smooth concrete floor and covered with epoxy. Every case we could find indicated that the turning radius for these systems was at a precise arc to allow a very smooth and very shallow turn. Therefore, we were faced with advancing the state of the art by developing a system to operate both indoors and outdoors, over irregular surfaces and open terrain, in naturally occurring environmental conditions such as wind and wet grounds, on moderate slopes which the vehicle would have to continuously work against, and to follow a cable that would be placed over unprepared surfaces by a human or a machine which would have no ability to control the height of the cable over the ground (raised by grass and small obstructions), nor any ability to control the direction or turning radius of the cable as the course is put down.

To accomplish this task a sensor was constructed which would dynamically measure the change in the strength of an electrically induced magnetic field as well as measure the rate of change in that field. Coupled with a software based control system the pair of magneto-strictive guidance sensors, shown in Figure 5, were able to work together to deliver a dynamically shifting voltage measurement to an analog to digital converter which, in turn, provided the onboard control computer with the digital equivalent of the voltages which had been read by the sensors.

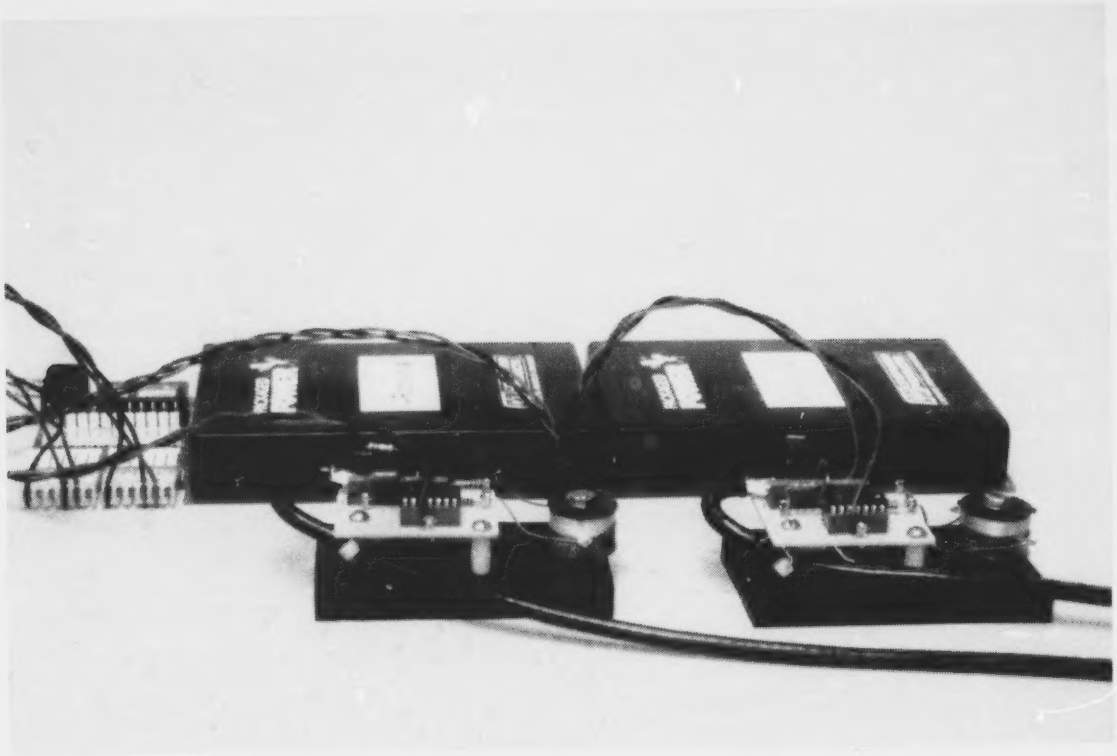


Figure 5. Magneto-strictive navigation sensors installed on robot.

The onboard control computer converted the data to a series of commands issued to the numerical motor controllers which dynamically controlled the drive motors to produce a smooth and continuous forward motion over the guide wire. The wiring diagram for the sensor is given in Figure 6. The drawing of the magneto-strictive guidance sensors' mounting bracket is presented in Figure 7. The bracket was mounted on the front of the hull of the Surveyor®, approximately four inches above the ground.

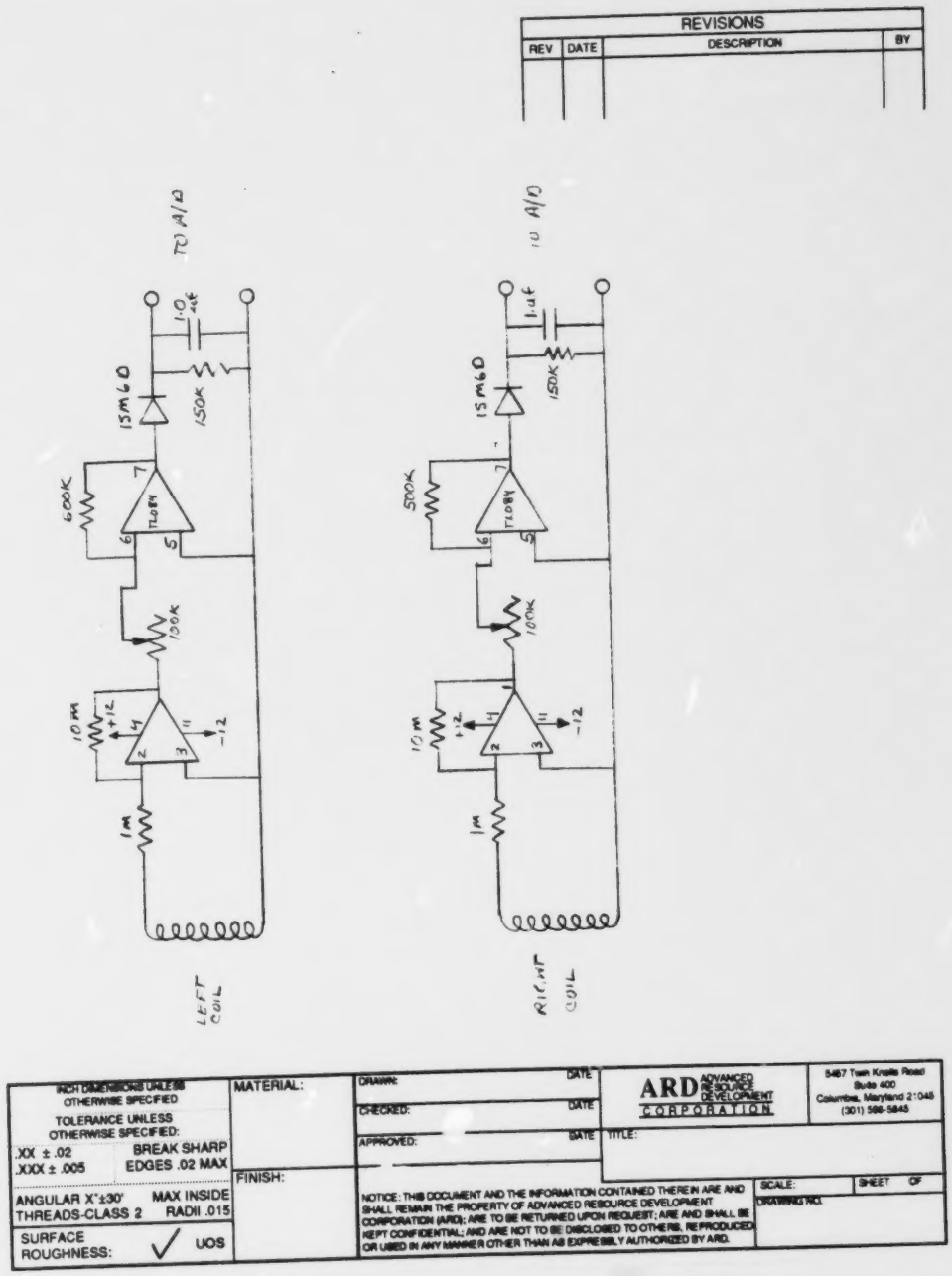
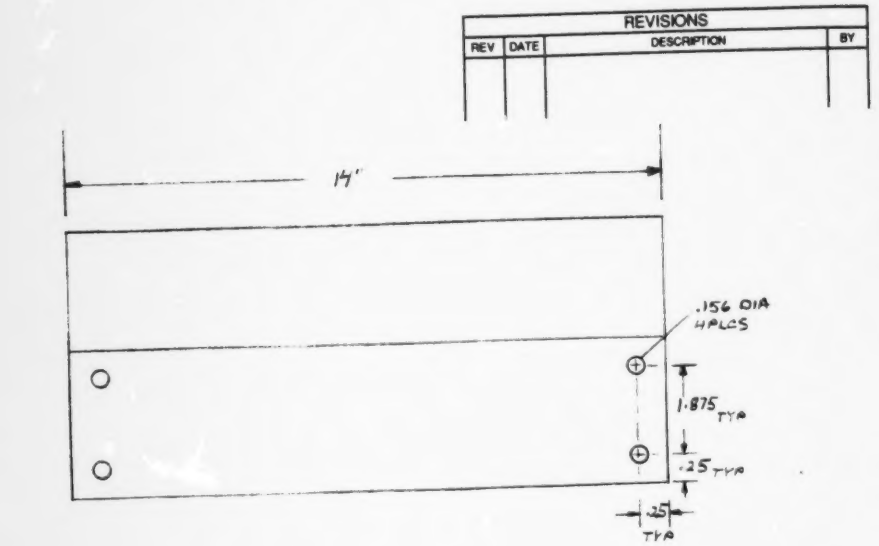
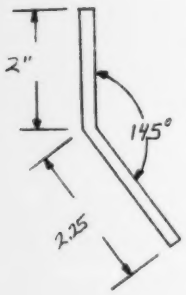


Figure 6. Navigation sensor wiring diagram.





INCH DIMENSIONS UNLESS OTHERWISE SPECIFIED TOLERANCE UNLESS OTHERWISE SPECIFIED: .XX ± .02 BREAK SHARP .XXX ± .005 EDGES .02 MAX ANGULAR X'±30' MAX INSIDE THREADS-CLASS 2 RADII .015 SURFACE ROUGHNESS: ✓ UOS	MATERIAL: .125 THK ALUM 5000 OR 6000 SERIES FINISH:	DRAWN: RBS 10/1/99 CHECKED: APPROVED:	ARD ADVANCED RESOURCE DEVELOPMENT CORPORATION TITLE: ADL-SURVEYOR GUIDENCE FLANGE	5487 Twin Knolls Road Suite 400 Columbia, Maryland 21045 (301) 596-5845 SCALE: NONE SHEET 1 OF 1 DRAWING NO.

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Figure 7. Navigation sensor mounting bracket drawing.

Photoionization Air Sensor--

In addition to the magneto-strictive sensors, we integrated with the robot system an HNU photoionization air sensor (Figure 2), which was provided through the air monitor work previously mentioned in this report, to measure the concentration of a simulated toxic substance (paint thinner) that might be found near a chemical spill or toxic waste site. The work plan originally stated that the sensor was to be mounted on top of the Surveyor hull and that the inspection camera was to be focused on the instrument's meter so that the concentration of the toxic substance could be observed and recorded on video tape. On closer inspection of the device, it was found that we could electronically integrate the air monitor into the existing sensor suite, convert the analog readout to a digital data stream and transmit the data from the robot to the control console over an RF modem link as part of the data stream being transmitted several times per second. With this accomplished, we modified the video display to reflect the presence of a new data output. Figure 8 shows an example of the video display during operation. In the upper left hand corner of the screen is where the concentration level of the toxic substance sensed by the air monitor is displayed. In Figure 8 that region of the screen reads "AIR: 19 PPM". In the center of the screen is the message that something was detected. It reads "SPILL DETECTED BY PHOTOIONIZER". The photoionization air monitor was mounted side-saddle on the vehicle with the intake probe suspended approximately eight inches above and pointed towards the ground.

Figure 8. Video display as seen through drive camera during the demonstration.

Obstacle Avoidance Sensor--

An obstacle avoidance sensor, shown in Figure 9, was developed as a safety feature along with an autonomous dead man switch to prevent avoidable accidents which could easily occur with the use of a 500 pound autonomous vehicle operating without any visual supervision on open terrain or in confined spaces. The obstacle avoidance sensor is actually a small sonar which generates and receives a sonic signal through the air and measures the time it takes for the signal to reach the closest solid object. A subroutine was developed and added to the control software, which converts this response time to a distance. If the distance measured by the system is less than five feet and the object is detected continuously for two seconds, (the time it takes for the vehicle to move two feet), Surveyor® will activate the automatic dead man switch which will command it to stop. The automatic dead man switch is also activated anytime there is a loss of signal from the guide wire.

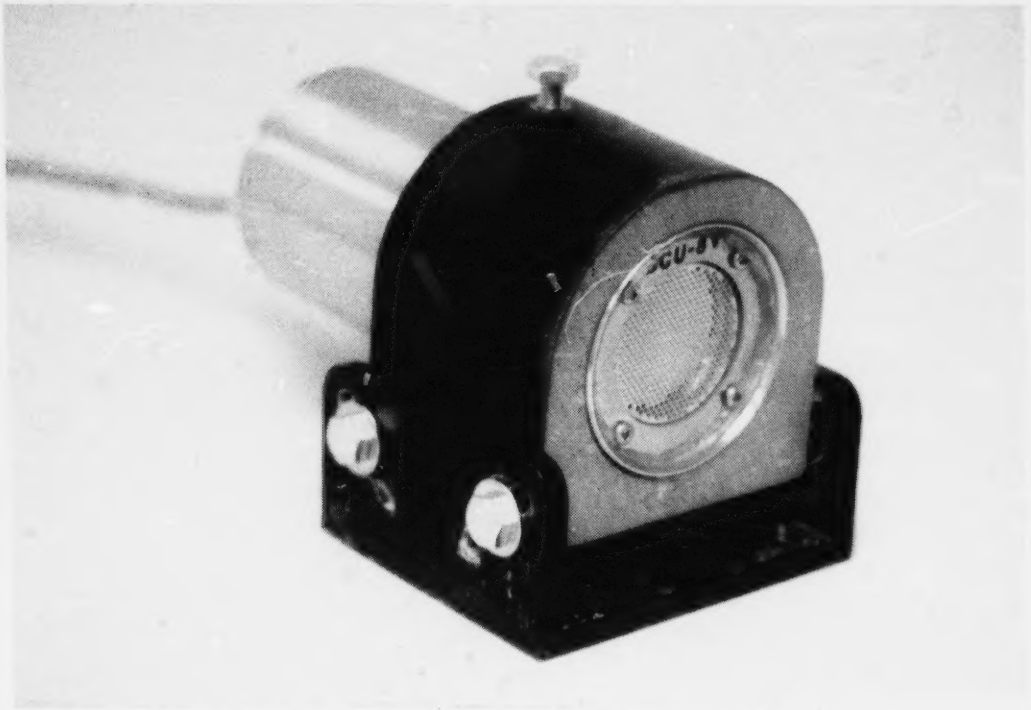

Figure 9. Obstacle avoidance sensor installed on robot.

Software Modifications

Several subroutines were developed and integrated with the Surveyor®'s Command program. The Command Software Flowchart illustrated in Figure 10 shows the conditions necessary for switching between manual/teleoperated mode and autonomous navigation mode, right and left turns, stopping and starting etc. This is the logic behind the software modifications to the system.

Software Description--

The Surveyor®'s Command program begins by initializing several components and variables. This process initializes the serial communication ports, the A/D board, several key variables and turns off all motors in the vehicle. Once the initialization process is complete the program goes into the main loop. The main loop is an infinite loop which can only be exited by turning off the vehicle or by pressing the letter "q" on the keyboard attached to the vehicle's computer during testing.

The main loop of the program is very simple. The first task in the loop is to wait for a full block of commands from the console by calling the "start_sync" routine. If the console is not sending any commands the vehicle sits and waits. If the console sends commands, the software checks to see if any communications errors occured through the "command_checksum" routine. Only if no errors occured are the console commands executed. If errors did occur, the program ignores these commands and waits for the next set of commands. If errors occur twice in a row, all motors on the vehicle are shutdown.

If no errors occur, the software looks to see if the emergency stop command was given. If it was, the vehicle is stopped. If the emergency stop command was not received, the system checks to see what mode of operation the vehicle is supposed to be in by calling the "Autonomous_Tracking" routine. All motor commands are then executed if the mode of operation is in teleoperation. If the mode is autonomous, the drive motor commands are ignored and the other motor commands, such as pan and tilt, are executed. Execution of these commands is accomplished in the "update_commands" routine.

The next step, reading data from the sensors, is performed regardless of the status of the communications. This is done so that the data can be stored onboard, if necessary, without interruption. If communications are stable, the digital commands are executed. These commands control functions like the zoom and focus of the inspection camera and the lifting of the arm.

If the operating mode is autonomous and communications are good, the software checks to see if the vehicle is on course and whether any objects are in its path.

The last step in the main loop transmits the data that has been collected by the sensors to the console so it can be displayed for the operator. This process is done regardless of communications status. Once completed, the program is returned to the beginning of the main loop to look for the next command block from the console. Table 6 lists the names of the new subroutines added to the Command program in this work assignment.

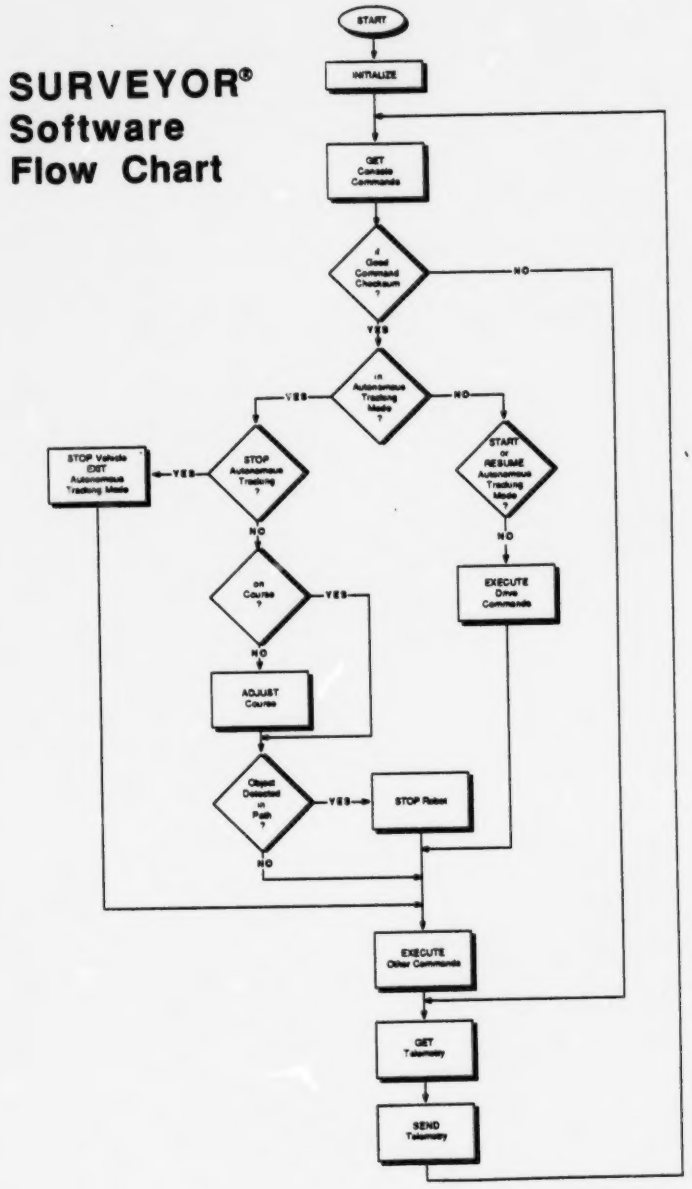

Figure 10. Command software flowchart showing the operation decision tree.

TABLE 6. SUBROUTINES ADDED TO COMMAND PROGRAM

Subroutine Names	Function
On_Course	Vehicle Navigation
Steer_Normally	Vehicle Navigation
Object_Detected	Obstacle Avoidance
Autonomous_Tracking	Operating Mode Selection
Spill_Detector	Toxic Substance Detection Switch
Magneto_Vantec	Dead Man Switch

Subroutine On_Course--The On_Course procedure is designed to keep the vehicle following the wire while in autonomous mode. The first operation performed is the reading of the two magnetic field sensors by calling the "read_telemetry" routine. The remainder of the routine involves nested if- statements to determine which of the three possible conditions exists. The first condition tested is for the vehicle losing contact with the wire. This condition is evident when the output from both sensors falls to zero. If this condition occurs, the routine increments a lost wire counter once for every cycle through this code that the sensors do not detect the magnetic field. If the lost wire counter exceeds a threshold of four counts, the vehicle's track velocities are set to zero which stops the robot. The second condition tested is to determine whether both sensors are detecting the magnetic field. This condition is evident when the output from both sensors is above zero. If this condition is satisfied, On_Course calls the Steer_Normally routine.

The third condition tested is whether the output from one sensor falls to zero and the output from the other sensor is above zero. When this condition occurs, the drive motor controlling the track of the side that detects the magnetic field is turned off resulting in a track velocity of zero while the drive motor of the other side is accelerated to the maximum track velocity. This will cause the robot to make a sharp turn towards the wire.

The final task of the On_Course routine is to execute the movement commands by calling the Magneto_Vantec routine and passing to this routine the left and right motor commands.

Subroutine Steer_Normally--The Steer_Normally routine is a dynamic steering algorithm which allows the vehicle to follow a magnetic field. This routine uses the right and left magnetic sensors to compute the straddle position of the vehicle about the wire and the velocity that the vehicle is travelling away from the wire. This routine begins by computing the difference between the left and right sensor output defined as the position error. The position error is used to calculate how fast the Surveyor® may be crossing the wire by subtracting the current position error from the previous position error, thereby calculating the velocity error. The position error and the velocity error are then used to compute a response which adjusts the separate track velocities thereby steering the robot over the wire. If the response is negative, the left track velocity

must be decreased. A negative response could be caused by the robot veering off to the right of the wire. If the response is positive, the velocity of the right track must be decreased. A positive response could be caused by the robot veering off to the left of the wire.

Subroutine Object_Detected--The Object_Detected routine is used to determine if an object is in the path of the vehicle. This routine is used when the robot is in the autonomous navigation mode. If an object is detected, a counter is incremented each cycle through this routine. If the counter reaches the threshold count (equivalent to a time duration of two seconds), the vehicle is stopped. Once the vehicle has stopped due to an obstructing object it will not resume operation until the robot has been reset. The operator must use the mode toggle switch on the control unit. By toggling from the autonomous mode to the teleoperated mode and then back to the autonomous mode, the robot is reset to the autonomous mode. If no object is detected during a cycle through this routine, the counter is set to zero.

Subroutine Autonomous_Tracking--The Autonomous_Tracking routine is used to look at the console commands and determine if the vehicle is to be in autonomous navigation mode or teleoperated mode. The second bit of the third command byte controls the vehicle's operating mode. If that bit is one, the robot should be in autonomous mode. If it is zero, the robot should be in teleoperated mode.

Subroutine Spill_Detector--The Spill_Detector routine looks at the value received from the air monitor. If the value was greater than zero, this routine signals that a spill was detected by setting a flag. The output from the air monitor is an analog signal in volts. The analog-to-digital board converts the input voltage to a 12 bit number. This number is normalized before being converted to parts per million, which is displayed on the console monitor.

MagnetoVantec--The MagnetoVantec routine toggles the dead man circuit when required and issues the drive motors their commands.

ROBOT SYSTEM TESTING

Testing was broken down into three broad categories for this project. These categories include the testing that was conducted at the ARD's facilities in Columbia, Maryland, and the indoor and outdoor tests conducted at the EPA site in Edison, New Jersey. This section will outline the tests which were conducted. Incremental problems were resolved after each test, or before the next tests were conducted. By the completion of the program all tests could be easily passed and all system functions were successfully demonstrated at Edison, New Jersey.

Component Testing

Testing began early in the system development effort with a series of bench mount tests as each component of the system was developed. Bench mount tests were conducted off the vehicle with no logic or electronic connections between the equipment being tested and the vehicle. Integration tests followed the bench mount tests. The integration tests tested the new equipment with logic and electronic connections between the new equipment and the vehicle. During the integration testing, the vehicle was elevated so that its tracks are not touching the ground while the response of the vehicle to various commands is evaluated. Once the integration testing was completed, the vehicle was placed on the ground/floor and the autonomous testing of the vehicle was performed. Many of the tests, particularly the integration and autonomous tests were

recorded on video tape for future reference. Within each of the types of testing, the tests were performed on an incremental basis. That is, once a particular test scenario passed, the next layer of capability was added to the system and then that was tested. In this way, an orderly and efficient testing of the system was performed increasing the likelihood of success at the demonstration. The next three sections briefly describe the tests that were performed during the bench mount, integration and autonomous testing of the system.

Bench Mount Testing--

- Bench tests of the bread board system using an oscilloscope to measure the sensitivity of the system,
- Bench test of the first magneto strictive sensor prototype (left sensor),
- Bench test of the second magneto strictive sensor prototype (right sensor),
- Bench test of both magneto strictive sensor prototypes on a dynamic separation and alignment apparatus,
- Bench test of both magneto strictive sensor prototypes on a dynamic separation and alignment apparatus after circuit modifications,
- Bench test of both magneto strictive sensor prototypes on a dynamic separation and alignment apparatus while adjusting the signal strength to each sensor,
- Bench test of the magneto strictive sensor system prototype on the dynamic separation and alignment apparatus in conjunction with the discrete voltage measurement routines,
- Bench test of the magneto strictive sensor system prototype on the dynamic separation and alignment apparatus in conjunction with the continuous voltage measurement routines and dynamic motor control routines,
- Bench test of the magneto strictive sensor system prototype on the dynamic separation and alignment apparatus in conjunction with the continuous voltage measurement routines, dynamic motor control routines, autonomous dead man functions and the obstacle detection sensor/routines,
- Bench test of the magneto strictive sensor system prototype on the dynamic separation and alignment apparatus in conjunction with the continuous voltage measurement routines, dynamic motor control routines, autonomous dead man functions, the obstacle detection sensor/routines and the photoionization air monitor data capture/display routines, and
- Bench test of the magneto strictive sensor system final design on the dynamic separation and alignment apparatus in conjunction with the continuous voltage measurement routines, dynamic motor control routines, autonomous dead man functions, the obstacle detection sensor/routines and the photoionization air monitor data capture/display routines.

Each of these tests were performed independent of the vehicle. The magneto strictive sensor system passed all of the tests before the next level of tests, the integration tests, were performed.

Integration Tests--

The integration tests were the first steps toward making the logic and electronic connections between the new equipment and software and the Surveyor®. The following integration tests were performed.

- Integration test of the magneto strictive sensor system final design on the Surveyor® vehicle and alignment apparatus in conjunction with the discrete voltage measurement routines,
- Integration test of the magneto strictive sensor system final design on the Surveyor® vehicle and alignment apparatus in conjunction with the continuous voltage measurement routines and dynamic motor control routines,
- Integration test of the magneto strictive sensor system final design on the Surveyor® vehicle and alignment apparatus in conjunction with the continuous voltage measurement routines, dynamic motor control routines, autonomous dead man functions and the obstacle detection sensor/routines,
- Integration test of the magneto strictive sensor system final design on the Surveyor® vehicle and alignment apparatus in conjunction with the continuous voltage measurement routines, dynamic motor control routines, autonomous dead man functions, the obstacle detection sensor/routines and the photoionization air monitor data capture/display routines, and
- Integration test of magneto strictive sensor system final design on the Surveyor® vehicle and alignment apparatus in conjunction with the continuous voltage measurement routines, dynamic motor control routines, autonomous dead man functions, the obstacle detection sensor/routines and the photoionization air monitor data capture/display routines.

Autonomous Tests--

Once the bench mount testing and integration testing was completed, the system was placed on the floor and all of the new capabilities were tested.

- Autonomous navigation tests using discrete tracking routines,
- Autonomous navigation tests using continuous and dynamic tracking routines,
- Obstacle avoidance tests,
- Photoionization air monitor data capture/display tests,
- Autonomous dead man function tests (loss of signal, obstacle detected, loss of communications, and

- Combined driving tests with all systems and all functions.

One humorous incident occurred during the autonomous testing of the obstacle avoidance system. The obstacle avoidance system had passed its bench mount and integration tests without trouble. Each time, the wave of a hand or arm in front of the device would shutdown the system. To be on the safe side, when it was tested in the autonomous mode, instead of using a person or anything else of value as the obstacle, some blocks of styrofoam padding, used when shipping fragile items, were placed on top of a cardboard box. This was to be the obstacle. The test was begun and the 500 pound robot moved toward the obstacle. The robot system never stopped and it ran over and crushed the obstacle. It took several minutes of head scratching and discussion before one of the team members realized that the styrofoam was absorbing the sound waves so that the sonar signal was not reflecting back to the sensor and, therefore, the system was not stopping.

The result is that any statement about the capability of the obstacle detection system should contain a qualifying sentence that states that the system will not detect stealth objects.

Full Scale Testing

Full Scale Indoor Tests--

Full Scale tests of a 300 foot test course were conducted late in the program when we were given access to one of the EPA warehouses in Edison. Prior to this, ARD was able to test the system over a twenty five foot course because ARD was in the process of moving to a new facility at the time when full scale testing was required. ARD had already moved out of its fabrication facility and its test facility which were the only practical locations to test the system over a 300 foot course. Fortunately this did not materially affect the performance of the system. At Edison, we ran seven trial runs prior to the demonstration. These trial runs were performed to test for:

- Guide wire detection,
- Wire following,
- Obstacle negotiation,
- Obstacle avoidance, and
- Toxic substance detection.

Initially the robot system had some small difficulties and we had to make a few last minute adjustments to the magneto-strictive guidance system. A close examination of the system found that a loose electrical connection was producing an intermittent sensor failure. Once corrected the system worked well in all cases except one (See Section 5 for details).

Full Scale Outdoor Tests--

Full Scale Outdoor Tests were also conducted at the EPA's facilities in Edison, New Jersey. In order to avoid a mid-winter outdoor demonstration or a slippage of the scheduled demonstration to warmer weather in March or April due to the unfortunate death of a key member of ARD's team, the schedule was altered to eliminate two weeks of testing that would have

normally been performed. Fortunately, the design of an autonomous navigation sensor with a dynamic sensitivity capability proved to be sufficiently robust to meet the rigors of outdoor operations on the first try. At Edison, we ran four trial runs prior to the demonstration. These trial runs were performed to test for:

- Guide wire detection,
- Wire following,
- Obstacle negotiation,
- Obstacle avoidance,
- Terrain negotiation, and
- Toxic substance detection.

Section 5, Robot System Demonstration, outlines the demonstration activities and Section 5, Demonstration Results, describes the results of the demonstration. It is important to note that the vehicle was able to drive non-stop through an overgrown field, following the guide wire at one foot per second, crawling over small obstacles, crossing over small trenches, detecting a toxic substance in a 30-35 mile per hour wind at temperatures less than 45 degrees F without human help or intervention. This test was successfully repeated during the demonstration. In all, we made four adjustments to the vehicle's speed (set through software control) to try to determine an optimum driving speed that would allow the photoionization sensor to detect a very small simulated spill. Our analysis of the vehicle speed is that it need not fall below one foot per second, which is too slow from a practical point of view, and could be increased to approximately four feet per second (equivalent to a walk or slow jog). Modest improvements are warranted in the overall sensor system configuration for outdoor operations such that external sensors are not subjected to the stress and strain of small trees and vines which could potentially damage the vehicle's external sensors.

SECTION 5

DISCUSSION AND RESULTS

ROBOT SYSTEM DEMONSTRATION

On December 15,1988 at the Environmental Protection Agency's Edison, New Jersey facilities, an autonomous air monitoring robot was demonstrated. The robot followed a guide wire around a 300 foot course outdoors and a 200 foot course indoors and reported the detection of a "toxic" substance without the benefit of human intervention or control. The following sections describe the presentation prior to the demonstration and the outdoor and indoor demonstrations.

Objective

The objective of the demonstration was to show that, with a minimum of modification, a commercially available mobile robot can perform air monitoring in an outdoor field and on a flat concrete surface such as a warehouse floor. The robot system was to perform a series of tasks. The tasks are listed in Table 7. Also in Table 7 is listed whether the task could be performed by the chosen robot or whether a modification to the robot was required.

TABLE 7. TASK VERSUS SYSTEM CAPABILITY

TASK	IMPLEMENTATION
Autonomous Navigation	System Modified
Object Detection	Sensor Available Software Modification
Small Obstacle Navigation	System Capability
Air Monitoring	Off-the-shelf Sensor Sensor Data Port Available Display Software Modification
Decontamination	System Capability
Stair Climbing	System Capability

The Surveyor® robot is a commercially available mobile robot which, in its base configuration, uses teleoperation as its mode of operation. It contains a sonar range detector which through software changes was converted to a large obstacle detector. Due to the design of its tracked mode of mobility, it has the ability to drive over small obstacles such as tree limbs and small rocks. In addition it can climb and descend stairs, which is useful for indoor surveillances. The system can be decontaminated with a high pressure hose. The autonomous navigation system was designed, tested and added to the Surveyor®. The air monitoring sensor, an off-the-shelf HNU photoionization monitor, was mounted on the Surveyor® and one of the available data ports

was used to collect the data. The onboard software was modified to accomodate all of the hardware changes. Because many of the requirements of this work assignment were either already a part of the Surveyor® system or could be fairly easily integrated with the Surveyor®, the objective of providing an autonomous air monitoring robot system with minimum modifications was achieved.

Demonstration Presentation

A presentation to approximately 30 members of the EPA's Risk Reduction Engineering Laboratory and Environmental Response Team was made by Uwe Frank of the EPA, Robert Rancatore of Arthur D. Little, Inc. and Eugene Silverman of Advanced Resource Development. Mr Frank presented the opening remarks and introduced Mr. Rancatore and Mr. Silverman. Mr Rancatore described the work assignment and the demonstration which was to be held right after the presentation. Mr. Rancatore also described a number of system enhancements to the modified Surveyor robot system which would help to make that prototype system one that could be implemented in the field. Several of the suggested enhancements are listed in Table 8. Some of these enhancements are included in the Recommendations section of this report.

TABLE 8. AREAS OF ENHANCEMENT TO THE CURRENT PROTOTYPE

AREA OF ENHANCEMENT	SUGGESTED ENHANCEMENTS
Duration of Operation	Recharging with current configuration (4 to 8 hours of operation)
	Add additional batteries (8 to 12 hours of operation)
	Pull a battery cart and reload
	Small propane engine to recharge batteries
	Gasoline powered with all terrain vehicle (ATV) suspension
Obstacle Avoidance	Include tactile sensors
	Allow continued operation if obstacle is removed.
Navigation Systems	IR Reflector method
	"Intelligence" to learn course
Suspension System	Wheeled instead of tracked system with an active suspension system
	Increase speed with wheeled system
Communications	"leaky coax" system instead of radio frequency transmission

The limitations of the prototype system were presented and are listed in Table 9.

TABLE 9. PROTOTYPE SYSTEM'S LIMITATIONS

PROTOTYPE SYSTEM'S LIMITATIONS
4 - 6 hour runtime
300 Foot video signal
50 F to 120 F ambient operating temperature
6000 pound maximum pull load
Maximum 45 degree incline
460 pound unit
1 foot/second maximum speed
10:1 zoom optics

Mr. Silverman presented an overview of the development of the Surveyor robot and briefly described its base design and capabilities.

At the conclusion of the presentations, there was a short discussion of an air monitoring system's use in the field, its cost and break even cost relative to actual air monitoring procedures currently performed. The general consensus was that a system of this nature would be able to pay for itself in a reasonably short period of time based on existing operations at the site.

Outdoor Demonstration

Outdoor Demonstration Description--

The outdoor demonstration of an autonomous air monitoring robot system was held in an open area adjacent to Building 245 at the EPA's Edison, New Jersey facilities. The area was overgrown with two to three foot grass, weeds and small trees and the surface was uneven with small gullies. In short, because it was not an area that had been manicured it was representative of the type of land that would be found at an actual waste site.

The guide wire was placed on the ground in a kidney shaped form with the perimeter somewhat wavy and uneven. A simulated toxic substance (paint thinner) was placed in aluminum pans alongside the wire so that the air monitor could detect the substance as it passed by mounted to the robot. The air monitor continuously updated the video display at the console with the number of parts per million of toxic substance that it found in the air as well as with a message that said it located the substance whenever the concentration exceeded 0 ppm. This was recorded on video tape for later analysis. At the same time, Rob O'Neil from ADL walked beside the robot with a hand held air monitor and verbally announced the simultaneous readings that his monitor was registering. His verbal readings were picked up by the onboard microphone and recorded with the video image. The comparison of the two readings will be discussed later.

Once all the observers of the demonstration arrived at the demonstration site, the robot was teleoperatively maneuvered onto the guide wire and then placed in autonomous mode by a flip of a switch at the control console. From that point on, the robot controlled its own navigation and negotiated the course in approximately 15 minutes. Along the way, the robot was required to navigate over small obstacles, record the concentration of the toxic substance and stop itself if a large obstacle was detected. The robot performed all of these tasks successfully and followed the guide wire without human assistance. There was some concern that sharp turns in the course would be a problem for the navigation system, but this problem did not develop.

During the demonstration, the onboard camera was active and the video and audio was transmitted to the command console where it was displayed on the monitor and recorded by a VHS Recorder. Superimposed on this same image was the concentration level of the toxic substance as reported by the air monitor. In addition to these taped portions of the demonstration, a separate VHS Camcorder was setup approximately 150 feet away from the demonstration site and it recorded the whole demonstration from there. More than two hours of film was edited to 15-20 minutes and delivered with the Final Report.

Indoor Demonstration

Indoor Demonstration Description--

Once the outdoor demonstration was completed, all of the equipment was moved into Building 245 which was a large warehouse. A similarly shaped course to the one outdoors, though smaller, was placed on the flat concrete floor. The robot system was once again maneuvered over the wire in teleoperation mode. It was then placed in autonomous mode and allowed to follow the guide wire. Once again aluminum pans of paint thinner were placed beside the wire at two locations so that the air monitor could detect the "toxic" substance as it passed by the pans while mounted on the robot. Rob O'Neil walked beside the robot with another hand held air monitor and verbally announced the readings that registered on his monitor. Like the outdoor demonstration, his verbal readings and the robot's readings were recorded on the video tape for later analysis.

The robot also navigated over small obstacles such as two-by-four studs. It should be noted that when the robot navigated over one of the small obstacles and then was to immediately turn to the right, it lost contact with the wire. This was the only malfunction by the robot during the demonstration. It successfully negotiated all of the other small obstacles during the demonstration. When the robot was moved indoors from the outdoor demonstration, it was put on a platform with wheels. When it was removed from that platform, the right hand sensor was caught and got jarred. It is believed, though not yet been proven, that the jarring it took caused an intermittent loose connection causing the malfunction, although the error did not occur again that day.

The rest of the tasks that were demonstrated outdoors were repeated indoors. A barrel was placed on the guide wire as a large obstacle. When the robot was within approximately three feet of the barrel, it stopped. The whole indoor demonstration was recorded on video tape and some of the scenes from the indoor demonstration will be included in the 15-20 minute video tape.

In addition, the robot was placed back in teleoperation mode and its ability to climb and descend a flight of stairs was demonstrated. The stairs were movable, wooden stairs used to enter one of the trailers that were stored in the warehouse. The Surveyor® was prepared for its climb by maneuvering the arm to correctly adjust its center of gravity. It then climbed the stairs without any problem. Once on the landing, the robot performed some skid maneuvering and arm location movements in preparation for its descent of the stairs. It once again performed without any problem.

The optics capability of the robot were demonstrated using the CCD camera. Pan and zoom were demonstrated with the picture displayed on the command console.

Prior to the stair climbing demonstration, a video was shown of the Surveyor® system at other demonstrations. They focused on the ability of the Surveyor® to perform in water up to the top of its hull and in a mud and water pit to simulate its ability to maneuver in a sludge-like material. The video tape also showed the ability to use a high pressure hose to decontaminate the robot. This was to be demonstrated live, however, due to the cold and windy weather conditions, the decision was made to show the video instead.

DEMONSTRATION RESULTS

The demonstration of an autonomous air monitoring robot using a commercially available mobile robot with a minimum of modifications was successfully performed in outdoor and indoor conditions. The next two sections describe the results of the demonstration and contain the comparison tables of the manually and autonomously collected air monitor readings. It should be noted that the range of values set on the air monitoring sensors was 0 to 20 ppm for the manually held sensor and 0 to 19 ppm for the autonomous sensor.

Outdoor Demonstration Results

As was stated above, the outdoor demonstration was performed successfully. All of the tasks, including autonomous navigation, small obstacle navigation, large obstacle detection and accurate reporting of the detection of a toxic substance were performed successfully. Table 10 contains the comparison of the autonomous and manually read outdoor air monitor readings. The pans of paint thinner were placed at two different locations, therefore there are two sets of comparisons. The first set show small differences between the readings. The robot system was designed to display a message on the console display screen when the air monitor sensor detected any "toxic" substances. A review of the video tapes showed that the autonomous readings displayed on the monitor followed the trend of the manual readings. For example, when it was announced that the levels of concentration were above the background level, the display showed the message that a toxic substance was detected. While the manual readings were reported to be off the scale, the display showed values of 19 ppm, the maximum value of the scale used during the demonstration.

The first set of data taken by the onboard system compared very well with the manual system. It was expected that there would be larger differences because the air monitors were different and because they were held in slightly different locations. Instead we received very good agreement with an RMS error of +/- 22%. This result is all the more remarkable given the fact that there was a very strong wind that was estimated to be blowing above 25 miles per hour.

TABLE 10. COMPARISON OF OUTDOOR MANUAL AND AUTONOMOUS AIR MONITOR READINGS

COMPARISON OF AIR MONITOR SENSOR READINGS (ppm)			
DATA SET #1		DATA SET #2	
MANUAL	ROBOT	MANUAL	ROBOT
0	0	0	0
16	19	10	0
20	19	10	0
20	19	6	0
7	10	7	0
20	10	5	0
10	3	0	0
3	2	--	--
0	0	--	--

The second set of data taken outdoors did not yield the same level of success that the first set did. In fact, as can be seen in Table 10, the onboard system did not detect any "toxic" substance. It is interesting to note, however, that the maximum manual readings were only half that of the first set of data and that the readings in the second set overall were much lower. It is believed that this was caused primarily due to the high wind and the direction of the wind. For the first set of data, the robot shielded the air monitors (both onboard and manual) from the wind, thereby allowing the sensors to detect the high levels of "toxic" substance. For the second set of data, the robot was on the downwind side of the substance and did not block the wind. For this reason it is believed that the onboard air monitor did not detect report any concentrations of the "toxic" substance.

The manually held air monitor, on the other hand, was partially shielded by the body of the team member walking beside the robot. It is believed that the partial shielding from the wind allowed the manually held air monitor to report the lower levels of concentration. Though the system did not report an accurate set of readings in the second location, it is felt that with the high wind that was experienced and given that the first set of data matched so well, the air monitoring performed outdoors was successfull.

The small obstacle navigation was performed successfully. A two by four piece of wood four feet long was placed across the guidance wire and the robot drove over it and continued on course without operator intervention. This was defined in the Demonstration Plan to be a successful outcome for small obstacle navigation.

The robot system travelled the complete course through tall grass and over very uneven ground and followed the guide wire without deviating from the wire or requiring operator intervention. Therefore, the autonomous navigation task was successfully performed.

At the end of the course, a barrel was placed on the guide wire to simulate a large obstacle in the path of the robot. As the robot approached to within approximately four feet it stopped, successfully performing the large obstacle avoidance task.

In summary, except for one portion of the air monitoring task which was severely affected by weather conditions, the outdoor demonstration of an autonomous air monitoring robot was successfully performed.

Indoor Demonstration Results

With the exception of the one incident, which will be described later, the indoor demonstration was successfully completed. All of the tasks including autonomous navigation, small obstacle navigation, large obstacle detection and accurate reporting of the detection of a toxic substance were performed successfully. Table 11 contains the comparison of the autonomous and manually read air monitor readings. Two sets of data were taken at different locations around the course. The demonstration was held inside of a warehouse, adjacent to several large loading dock doors which were open to allow additional light to enter the warehouse and to allow some ventilation of fumes caused by a gas heater which had been running on the previous day. The location where the first set of data was to be recorded was directly in front of one of the open doors. This caused the wind to once again play a part in the demonstration, though with not near the same results as outdoors. As can be seen from Table 11, each set of readings compare very well with the exception that the first set of onboard readings continue to detect a toxic substance in the air for approximately 12 seconds after the manually held readings have returned to background readings. The robot system was travelling downwind of the pans of the "toxic" substance and it is believed that the wind carried the fumes to the air monitor where it continued to detect a low concentration level of the substance. The onboard system and the manual system reached the same maximum value and began detecting the substance at almost the same time.

The second set of data taken indoors was more conclusive than the first. The location of the pans of "toxic" substance were much further away from the doors and were not affected by the wind. The readings match extremely well with the beginning of detection, the ending of detection and the rise and fall of the levels of concentration tracking very well. Based on these readings, we can conclude that the indoor air monitoring task was successfully performed.

The small obstacle navigation test was performed with one minor problem. The robot lost contact with the wire and came to a stop after navigating over a two by four that was placed across the guide wire. It is not known exactly why the robot did not stay on course this time. There was an incident which occured while the robot was being transported from the outdoor demonstration to the indoor demonstration in which one of the navigation sensors was struck. It is possible that a connection became intermittent causing a problem after the robot crossed the obstacle but it is not known with any certainty that this caused the problem. This mishap did not happen again during the demonstration.

TABLE 11. COMPARISON OF INDOOR MANUAL AND AUTONOMOUS AIR MONITOR READINGS

COMPARISON OF AIR MONITOR SENSOR READINGS (ppm)			
DATA SET #1		DATA SET #2	
MANUAL	ROBOT	MANUAL	ROBOT
0	0	0	0
20	19	20	19
20	19	20	19
20	19	20	19
10	19	20	19
0	5	20	19
0	2	5	5
0	2	3	2
0	0	0	0

The robot system travelled the entire course, with the exception as stated above, without requiring operator intervention. The autonomous navigation system performed successfully indoors.

To test the large obstacle avoidance system, a barrel was placed on the guide wire in the path of the vehicle. When it was approximately four feet from the obstacle it stopped, successfully performing the obstacle avoidance test.

ROBOT SYSTEM SPECIFICATIONS

The autonomous air monitoring robot which was successfully demonstrated as a part of this work assignment was developed from an existing robot with a minimum of modifications. The system that was demonstrated was a prototype system. The navigation guidance sensors were attached to a bracket on the outside of the hull instead of inside the hull where they would be safer from the elements, the air monitoring device was hung on the robot side-saddle with the help of a bracket and duct tape held the air monitoring device's wand in place. These prototype modifications were made in this manner because it was decided that the water-tight hull of the robot would not be compromised for this demonstration. It is obvious that a prototype system could not be field implemented in this form. In addition, there were a few areas where additional modifications to the baseline robot would be essential to make it the system that the EPA is interested in field implementing. This section of the report lists several modifications to the baseline system. The modifications have been grouped by function or sub-system (i.e., navigation, communication, etc.). Table 12 contains a list of the functions/sub-systems where modifications are suggested.

TABLE 12. AREAS OF MODIFICATIONS AND ENHANCEMENTS FOR EPA ROBOT

FUNCTIONS/SUB-SYSTEMS
Navigation
Run Duration
Communication
System Operation

Baseline System Specifications

The baseline system specifications for the robot vehicle, supervisory control station, onboard cameras and sensors and autonomous navigation system specifications can be found in Table 13. The overall weight and dimensions of the robot vehicle, its current traveling speed and run duration are listed there.

TABLE 13. SURVEYOR BASELINE SPECIFICATIONS

Robotic Vehicle	Metric Units	English Units
Weight	227 kg	500 lbs
Length	1145 mm	45 in.
Width	560 mm	22 in.
Height	685 mm	27 in.
Vertical Clearance	760 mm	30 in.
Climbing Attitude Limit	42 deg.	42 deg.
Speed	0.30 m/s	1 ft/sec
Running Time	4-6 hours	4-6 hours
Construction (Hull/Top/Plastic)	Steel/Alum./Delrin	Steel/Alum./Delrin
Supervisory Control Station		
Weight	113 kg	250 lbs
Height	1830 mm	72 in.
Width	660 mm	26 in.
Depth	485 mm	19 in.

TABLE 13. (Continued)

Cameras	
Inspection Optics	High resolution Charged Couple Device (CCD) camera with a 10:1 power zoom lense, remote zoom and focus, auto iris, white balance, pan and tilt.
Drive Optics	Two high resolution CCD cameras optically aligned for stereo vision capability, auto iris, white balance. Remote zoom and focus are optional.
Rear View Optics (Optional)	One high resolution CCD camera positioned for rear view capability, auto iris and white balance.
Environmental Sensors	
Radiation Temperature Humidity Range Finder Acoustics Options	Digital Ion Chamber Air temperature sensor 0-100% range Sonar Bi-aural/stereo high fidelity microphones Thirteen expansion channels are available
Navigation Sensors	
Output Input Distance above ground Distance between sensors	0 - 5 volts (in 2 stages) Coil output maximum 50 - 60 millivolts first stage amplifier, 0.5 - 0.6 volts second stage amplifier, 5 - 6 volts ground, -12 volts, +12 volts 4 inches 6 inches
Magnetic field	10 amperes, 60 Hertz, 10 volts AC

Field Robot Specification

Any field robot must be designed to withstand the environment it is to navigate through. This may include terrain overgrown with tall grass and small bushes and saplings. It was obvious from the demonstration that leaving the sensors exposed to these elements could lead to damaged or in-operative sensors. Installing the navigation sensors and air monitor inside the robot hull would increase the reliability of the sensors and reduce the chances of their being damaged during transportation and operation of the robot. Therefore, the field robot would have all

of the sensors, except the magneto- strictive coils, installed inside the Surveyor. The magneto strictive coils would be installed in the skid bar in front of the Surveyor. The existing sensors would be re-designed to fit in the skid bar.

Navigation Enhancements--

In the current work assignment an autonomous navigation system was installed and demonstrated using a modified Surveyor robot. During the demonstration it became apparent that additional changes to the navigation system would have to be made if the system were to be implemented in the field. Table 14 lists the suggested modifications to the navigation system.

TABLE 14. SUGGESTED NAVIGATION ENHANCEMENTS

NAVIGATION ENHANCEMENTS
Increase vehicle speed, change drive motors and add reduction gears to support speeds to 10 feet per second
Upgrade onboard computer
Investigate active suspension for all terrain use
Improve obstacle avoidance system
Add software to locate the guide wire after contact is lost

Increase Vehicle Speed and Change Drive Motors-- The speed of the robot was set at 1 ft/second for the demonstration. The demonstration showed that the speed of the robot should be increased to that of a human's walk or slow jog, which is in the range of 5 - 10 feet per second. The current drive mechanism on the Surveyor® cannot reliably propel the robot at speeds of 10 feet per second. Therefore, drive motors and gear reducers must be added to support the higher speeds. In order to attain these speeds, several of the other modifications listed in Table 14 should also be performed. Each one is detailed separately below.

Upgrade Onboard Computer-- In order to process the guide wire signals fast enough to handle the increase in forward motion of the vehicle, the robot's onboard computer must be upgraded, at a minimum, to a class 80286 computer and possibly an 80386 computer, depending on the final speed of the vehicle and other processing requirements.

Investigate Active Suspension-- The Surveyor® has a tracked suspension primarily because historically it has been used indoors where the requirement for climbing and descending stairs is emphasised. An active all-terrain suspension would enable the robot to travel at higher rates of speed and, at the same time, negotiate over small obstacles. Therefore, we suggest an active all-terrain suspension be used for an autonomous, field-implemented air monitoring robot.

Improve Obstacle Avoidance System-- The obstacle avoidance system could be improved. Currently the system stops and shuts the robot down when an obstacle is determined to be in the way. The system could be made to check that the obstacle continues to exist after it has been detected. If the robot no longer sees the obstacle, then it should continue on its course. This will eliminate the need to re-start the system because someone accidentally walks in front of the robot or if an animal were to cross the robot's path.

Guide Wire Location Software-- The current demonstration showed that the system's autonomous navigation system could be counted on keeping the robot on track over 95% of the time. Currently, the robot stops and sends a message to the command station if it loses contact with the wire. Though stopping the robot under these circumstances keeps the robot from causing harm to itself and possibly others, a method for re-establishing contact with the wire should be included in the software. This would minimize the number of distracting and potentially time consuming and costly interruptions the work team would encounter requiring one of them to manually re-establish contact between the robot and the wire. One example of a method for accomplishing this would be to make the vehicle move in a slow right-hand turn through a full 360 degree circle in an attempt to re-establish the wire. If the wire was not found, then the robot would repeat the procedure turning to the left. Once the wire is found, the robot would continue its monitoring. If the wire is not found, then the robot would send a message to the console, as well as provide an audible alert signal for the operator.

Run Duration--

The prototype system used in the demonstration has a run duration of 4-6 hours before requiring that the batteries be recharged. For most air monitoring projects, 4-6 hours is not sufficient to supply adequate monitoring at waste sites. In the summertime, when the number of daylight hours increases to 12-14 hours, it would useful to have a robot which could monitor the air for that long and possibly longer. In addition, increasing the speed of the robot, the terrain of the waste site and the outdoor temperature (particularly in colder climates) are likely to put an added drain on the batteries, further reducing the runtime duration of the current system. Table 15 lists the modifications and enhancements to help lengthen the number of hours that the robot could be used before requiring that the batteries be recharged.

TABLE 15. RUN DURATION ENHANCEMENTS

RUN DURATION ENHANCEMENTS
Install longer life batteries
Develop a battery cart
Investigate alternative propulsion systems

Install Longer Life Batteries-- One method of prolonging the runtime of the robot is to install new, longer life batteries. Assuming that batteries of long duration exist that will meet the

14+ hours of operation required and will fit into the existing hull of the robot, this would require the minimum modifications to the system to prolong runtime. Investigation into the availability of such batteries would have to be performed.

Develop a Battery Cart-- The present architecture of the robot is limited in the number of batteries that can be used to power it by the amount of space available for storage in the hull. The robot's runtime could be dramatically increased if a separate battery cart is designed which would be towed behind the robot and which would hold the number of batteries needed to extend the runtime to as much as 24 hours. In addition, changing the batteries could be made easier with the battery cart than presently with the robot itself. The design of the battery cart should include the ability to easily decontaminate it with high pressure water.

If more than one cart were available, one could be in use while the other is being recharged. In this way there would never be a shortage of battery power. Overnight charging of a single battery cart is also an option.

Alternative Propulsion Systems-- For longer term running of the robot, alternative propulsion systems should be looked at which either directly power the robot, such as a small gasoline or other fossil fuel engine or constantly charge the batteries while the robot is used, such as with a small propane engine. A propulsion system of either of these types should allow for several days of runtime without requiring battery recharge or fuel refill.

Communications--

One limitation of the prototype which must be overcome before the system can be implemented in the field is the method of communication with the robot by the operator. Presently, the operator uses a control console which communicates using radio waves of a particular frequency. The size of the transmitter is a quarter of a watt which means its range is very limited. It is a fairly simple procedure to increase the size of the transmitter to increase the range of the system. This, however, requires an FCC license, which is a rather difficult and involved process.

An alternative method of communicating with the robot in a remote mode is to install a "leaky coax" communication system on the robot. This type of communication system utilizes the coax cable as an antenna to transmit and receive data. Such a system would be designed and added to the prototype robot system. The coax cable would be strung around the perimeter of the site, such as on fence posts, and the robot system would use it to communicate commands, transmit data and perhaps be used to guide the robot.

A system of this type would be mobile, easily implemented at each waste site and would not require any special licenses.

System Operation--

Several enhancements to the system which would improve its operation or provide additional control of the system were also identified during and shortly after the demonstration. They are listed in Table 16.

TABLE 16. SYSTEM OPERATION ENHANCEMENTS

SYSTEM OPERATION ENHANCEMENTS
Add battery powered RAM to replace system EPROMS
Add external keyboard port
Allow user-defined vehicle speed between 1 and 5 MPH
Modify toxic substance detection software to turn on an alarm when the concentration of a toxic substance exceeds a user-defined level.
Develop a temperature regulator for the interior of the Surveyor to protect the onboard computer during cold weather operation.

Battery Powered RAM-- The prototype system uses EPROMs to store the program that the onboard computer uses to control the robot. In general, EPROMs (Erasable Programmable Read Only Memory) are well known entities used in many thousands of products. However, they can be very difficult to implement. Generally, the software that is written is "burned" into the chip or chips and they are installed in the computer. The problem is EPROMs are temperamental. The slightest problem, such as static electricity, can cause severe problems when burning the program into the chip. One solution to this problem is to add a battery powered RAM (Random Access Memory) board or bubble memory to the onboard system which would allow faster changes to the software because the extra burn-in step is not necessary. In addition, the battery powered RAM is not nearly as temperamental as the EPROM is.

Add Keyboard Port-- Another modification to the prototype system which would aid in the development of future systems is to add a keyboard port to the hull of the Surveyor®. Presently, the top of the Surveyor® must be removed to attach a keyboard for programming and testing purposes. By having a keyboard port through the back of the hull, programming and testing of the future systems will be much easier and less time consuming. In addition, the system can be tested in its watertight mode keeping dirt and dust out of the hull of the Surveyor®. In some of the environments that the systems are targeted to be used, this can be a very important feature should a system require maintenance or testing.

User-defined Vehicle Speed-- The software of the robot system should be changed to allow the user to select the speed that the vehicle is to travel. The range of vehicle speeds must be compatible with the abilities of the navigation system. Currently the speed of the vehicle is set in the onboard computer's control program.

Toxic Substance Detection Software-- The robot's software that detects the presence of a toxic substance should be modified to generate an audible sound and light a visual flashing light whenever it senses a concentration of a toxic substance above a user-defined threshold. In addition, the location where the high concentration was located, relative to the navigation guide wire, should be recorded so that additional investigation can be made easily.

Temperature Regulator-- The Surveyor® system has a low operating temperature limit of 40 degrees F. due to the operating limitation of the onboard computer. This limitation is a problem when the robot has been stored in a cold place and is allowed to cooldown to a steady-state temperature below 40 degrees F. This problem can be solved by regulating the temperature inside the hull before turning on the electronics. This can be done by heating the inside of the hull with strip heaters. The power used by the strip heaters should be taken into account when determining the number of batteries to be used to power the robot system.